**Published online August 1, 2005**



# Herbage Nitrogen Recovery in a Meadow and Loblolly Pine Alley

David M. Burner* and Charles T. MacKown


## ABSTRACT

**Herbage in conventional pasture and agroforestry systems is managed for microclimate and spatial differences inherent to these systems, but managers have scarce data on which to base their decisions. Our objective was to measure herbage N fertilizer recovery at two sites, an unshaded meadow and a shaded alley in 10-yr-old loblolly pine (*Pinus taeda* L.). The test was conducted on a Leadvale silt loam soil (fine-silty, siliceous, semiactive, thermic Typic Fragiudult) near Booneville, AR, in 2002 and 2003, with tall fescue (*Festuca arundinacea* Schreb.) the predominant herbage species. Fertilizer N was broadcast as split-applications at six rates (100 kg ha$^{-1}$ increments from 0 to 500 kg ha$^{-1}$ yr$^{-1}$). The meadow and pine alleys had sufficient herbage yield for rotational livestock production. Cumulative herbage yield (CHY) in the meadow was much more responsive to added N than pine alley herbage, but average cumulative fertilizer N (CFN) recoveries were only 38% and 12%, respectively. A shallow fragipan, low available soil P ($\leq$ 6 $\mu$g g$^{-1}$), depletion of soil water in July to September (both sites), and low solar irradiance (pine alley) were likely contributors to low fertilizer N recovery and herbage productivity. Because of poor herbage yield response and substantial accumulation of soil mineral N (62 to 237 kg ha$^{-1}$) in pine alleys fertilized with $\geq$200 kg N ha$^{-1}$ yr$^{-1}$, only maintenance levels of fertilizer N ( $\leq$ 100 kg ha$^{-1}$) should be applied to similar sites. For these same reasons, yearly applications of fertilizer N > 300 kg ha$^{-1}$ yr$^{-1}$ are not recommended for meadows similar to the study site.**


THE CONVERSION of marginal crop and pasture land to tree crops is becoming increasingly attractive as an economically rational use of land resources (Grado et al., 2001; Harwell and Dangerfield, 1991), which is stimulated in part by static farm receipts, increased demand for timber products, and government cost-share incentives (Haynes, 2003; USDA-NASS, 2002; Zinkhan and Mercer, 1997). Loblolly pine is well suited for use in temperate agroforestry because of rapid growth on sites with low inherent soil fertility and minimal fertilizer inputs (Schultz, 1997).

Plant growth in an agroforestry environment is constrained by crop–tree competition for light, shade, and soil nutrients. Understory plants respond to this competitive environment through morphological (Devkota and Kemp, 1998–1999) and physiological (Givnish, 1988) adaptations. There also can be drastic changes in various soil properties within the first years of tree establishment: increased soil N mineralization and nitrification and decreased soil pH (Parfitt et al., 2003; Ross et al., 2002). These effects can persist in stands after 25 yr of growth (Saggar et al., 2001).

Some crop plants adapt well to growth in agroforestry systems. Alley cropped maize (*Zea mays* L.) can accumulate 2.8 times the whole-plant N of a non-agroforestry crop, about 15% of the increase coming from decomposing tree mulch (Haggar et al., 1993). Tall fescue is shade tolerant (Burner, 2003; Lin et al., 1999) and responds to supplemental fertilization in a silvopasture on marginal land (Brauer et al., 2004). Without fertilization, however, its production as an alley crop appears to be unsustainable (Burner and Brauer, 2003).

Considerable herbage can be produced in the understory during the tree rotation (Fribourg et al., 1989; Lewis and Pearson, 1987), and crop and tree productivity can be increased with supplemental fertilization (Clason, 1999; Schultz, 1997). To our knowledge, fertilizer N recovery has not been examined for cool-season grasses in temperate pine agroforestry, as has been done in open pastures (Hall et al., 2003; Staley et al., 1991; Stout and Jung, 1992; Zemenchik and Albrecht, 2002). Our objective was to measure herbage recovery of fertilizer N in meadow and pine alley sites. We hypothesized that herbage would recover less N in a pine alley than an unshaded meadow, because of the combined constraints of low solar irradiation, water stress, and tree competition.

## MATERIALS AND METHODS

The experiment was located (35°05′ N, 93°59′ W) about 150 m above sea level on Leadvale silt loam soil. In spring 1994, 1-yr-old loblolly pine seedlings were planted for timber production at 2.4-m spacing in rows 3.6 m wide oriented east–west. There were 995 trees ha$^{-1}$ in 2002. This site will be referred to as the pine alley. There was no record of herbage botanical composition at tree planting, but pastures of the region typically are a complex mixture of cool- and warm-season grasses and forbs (Burner and Brauer, 2003).

Neither site was amended with lime or fertilizer since 1994. The meadow treatment (no trees) was located about 1.7 km from the pine alley treatment. Topsoil (15-cm depth) at each site was analyzed before initiation of the study by standard methods of the University of Arkansas Diagnostic Laboratory (pH in 1:2, soil/water, w/v; Mehlich III extract for P and K; KCl extract for $NO_3$–N). Hydrated lime [$Ca(OH)_2$] was broadcast applied at 2240 kg ha$^{-1}$ to the pine alleys in December 2001 to raise the pH of the pine alley site to a level similar to that of the meadow, and P (100 kg ha$^{-1}$) and K (140 kg ha$^{-1}$) were

Product names and trademarks are mentioned to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA does not imply the approval of the product to the exclusion of others that may also be suitable.

D.M. Burner, USDA-ARS, Dale Bumpers Small Farms Research Center, 6883 South State Highway 23, Booneville, AR 72927; C.T. MacKown, USDA-ARS Grazinglands Research Lab., 7202 W. Cheyenne St., El Reno, OK 73036. Received 15 Oct. 2004 *Corresponding author (E-mail:dburner@spa.ars.usda.gov).

Published in Crop Sci. 45:1817–1825 (2005).
Forage & Grazing Lands
doi:10.2135/cropsci2004.0607


**Abbreviations:** CFN, cumulative fertilizer N; CHY, cumulative herbage yield; CMN, cumulative net mineralized soil N; CNY, cumulative N yield; PAR, photosynthetically active radiation.

applied to both sites in December 2001 and 2002. Slope was ≤5% at each site.

In fall 2001, accumulated herbaceous growth was clipped at 7.6 cm and removed. Lower branches of trees were pruned to about 2-m height (ground level to first live branch) in December 2001, leaving about 70% of the tree crown unpruned. Pruned branches were removed from the site. In 2002 and 2003, $NH_4NO_3$ was broadcast applied in split applications (one-third rate in March, May, and September) at 0, 100, 200, 300, 400, and 500 kg N ha$^{-1}$ yr$^{-1}$. The N fertilizer treatments were arranged in a randomized complete block design with three replicates. Treatment plots measured 2.5 by 6 m and were separated by buffers ≥ 1.5 m. In the pine alley, plots were positioned between tree rows, so <50% of the root zone of any tree was included within the plot boundary. Each replicate was separated by at least one unfertilized, 3.6-m-wide pine alley (Fig. 1).

Air temperature, photosynthetically active radiation (PAR), and rainfall were recorded 1 m aboveground in the meadow and pine alley sites at 0.5-h intervals between March and October during 2002 and 2003. The PAR was measured with a Model 3668 quantum light sensor (Spectrum Technologies, Inc, Plainfield, IL) at $\lambda$ = 400 to 700 nm. The PAR sensor was stationary in the meadow, but was moved at weekly intervals among pine alley plots to provide a representative PAR measurement in the presence of transient sunflecks (Pearcy, 1990). Long-term air temperature and rainfall data were from a Booneville, AR, weather station (NOAA, 2002a) located about 7.0 km east of the experimental sites.

Volumetric soil water was monitored using Trime-time domain reflectrometry (MESA Systems Co., Medfield, MA) using the manufacturer's calibration for mineral soil. An access tube was permanently installed in each plot receiving 0 and 500 kg N ha$^{-1}$. Soil water was recorded at about weekly intervals at 10-, 35-, and 70-cm depths, and averaged across depths. Height of randomly selected trees along plot boundaries was measured with a clinometer. Trunk diameter at 1.3 m above ground surface (dbh) was measured with a diameter tape. Basal area was calculated from mean dbh (Avery and Burkhart, 1994).

Botanical composition was estimated visually before plot harvests as the relative dry mass contributed by predominant species components. Plots were harvested on 2 May and 17 Oct. 2002, and 6 May, 23 June, and 15 Oct. 2003. A swath (0.6 or 0.87 m wide by 6 m long) of herbage was cut mechanically with either a sickle bar or rotary mower, depending on harvest date, at a stubble height of 7.6 cm. Herbage was harvested at 7.6 cm to allow for regrowth without excessive stress and to simulate herbage removal by livestock. Dry matter yield was calculated from a sample dried to constant weight in a forced-draft oven at 60°C. Before fall harvests, pine alleys were raked to remove some of the fallen pine needles. Herbage outside the sampled area was cut to a stubble height of 7.6 cm and removed from the plot.

Immediately after each herbage harvest and before N application, two soil cores (6.4-cm diameter by 60 cm long) were obtained with a Giddings hydraulic probe (Giddings Machine Co., Ft. Collins, CO) from each plot, sectioned into three layers (0–10, 10–30, and 30–60 cm depth), and combined by depth. Soil was air-dried and ground in a mortar to pass a 1.4-mm screen. All soil samples were analyzed for mineral N by extracting with 1.0 *M* KCl and measuring $NH_4$–N by automated diffusion coupled colorimetry (Tecator, 1984) and $NO_3$–N by Cd reduction coupled colorimetry (Tecator, 1983) using a FIAstar 5010 flow injection analyzer (Foss Tecator, Höganäs, Sweden). Samples collected in May 2002 and Octo-

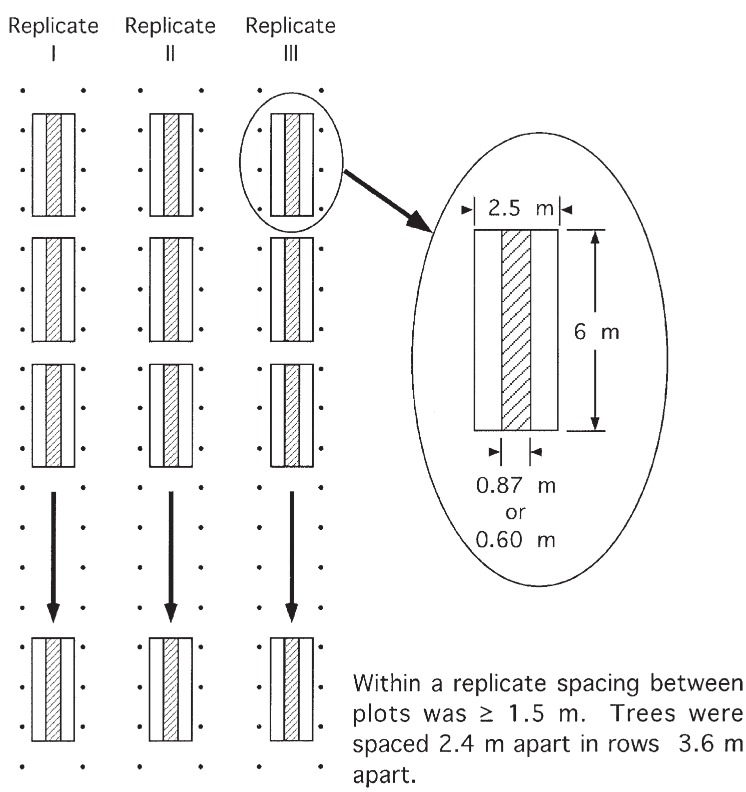


**Fig. 1. Orientation of N fertilizer treatments within loblolly pine alleys. Trees were spaced 2.4 m apart within rows and 3.6 m between rows. One or more buffer alleys separated replicates. The N treatments were randomized within replicates. Herbage and soil samples were collected from the central region (striped rectangle) of each plot. Only three of the six N treatment plots are shown; heavy downward arrows represent plots not shown.**

ber 2003 were also analyzed for 1.0 *M* KCl extractable Al (Dougan and Wilson, 1974), Mehlich III extractable P (Mehlich, 1984), total C and N by Dumas combustion (VarioMax, Elementar Americas, Inc., Mt. Laurel, NJ), and pH (1:1, soil/water, w/v). Herbage total N was determined by Dumas combustion (Leco FP428, Leco Corp., St. Joseph, MI). Trees were not sampled for foliar yield or N.

Soil chemical data for May 2002 and October 2003 were analyzed as a randomized complete block design by site using the mixed linear model, PROC MIXED (Littell et al., 1996; SAS Institute, 1998). Date (1 df), N rate (5 df), soil depth (2 df), and their interactions were fixed effects. Replication (2 df) and its interactions were random effects. Total mineral N in the 0- to 60-cm depth profile for May 2002 and October 2003 also was analyzed as a randomized complete block design by site using a mixed linear model (Littell et al., 1996) in which date (1 df), N rate (5 df), and the date $\times$ N rate interaction were fixed effects. Replication (2 df) and its interactions were random effects.

Total rainfall and mean air temperature for the March to October growth interval (Fig. 2) were computed on a month within year basis and compared to the long-term (1971–2000) mean for Booneville (NOAA, 2002a). The PAR data set contained about 28 000 observations for the 8-mo growth interval at 0530 h to 1900 h. Data of each site were analyzed separately using a mixed linear model (Littell et al., 1996) with year (1 df), month (7 df), time of day (28 df), and their interactions (203 df) as fixed effects. Day within month and year (480 df) was the random effect. The year $\times$ time of day interaction was analyzed for each site using polynomial regression analysis (SAS Institute, 1998). Only polynomial terms with coefficients significantly different ($P \leq 0.05$) from 0 were retained.

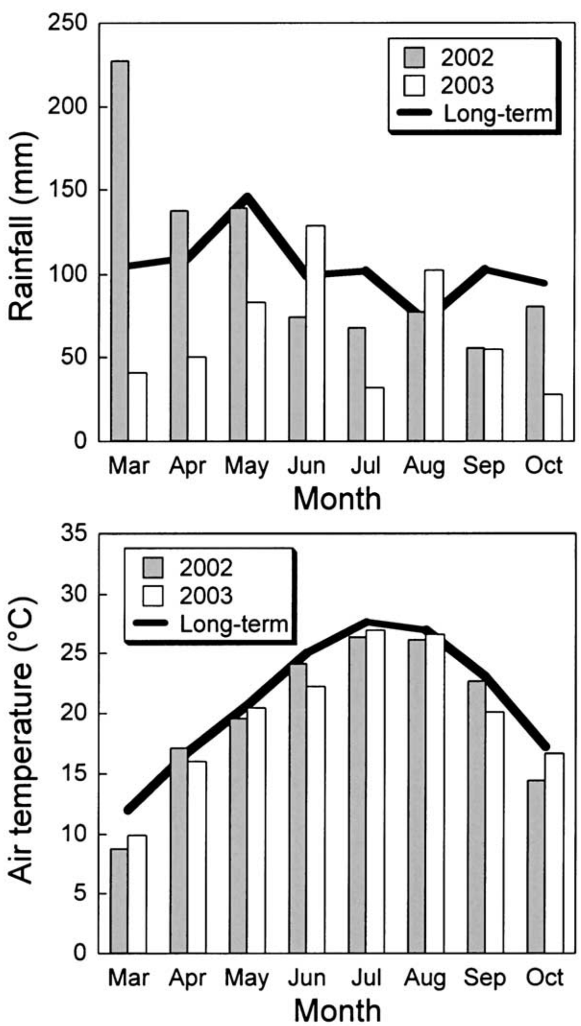


**Fig. 2. Rainfall totals and mean monthly air temperatures for the March to October growth interval in 2002, 2003, and the long-term mean for 1971 to 2000 (NOAA, 2002a) at Booneville, AR.**

We assumed there was some unknown quantity of carryover N between successive harvests and years (Vanotti and Bundy, 1994), which necessitated calculation of cumulative effects (Staley et al., 1991). Nitrogen use components were calculated by the following equations:

$$\text{Cumulative N yield (CNY, kg ha}^{-1}) = \text{CHY} \times \text{herbage N (g kg}^{-1})$$

Cumulative herbage yield was the sum of herbage yield for each plot at successive harvests.

$$\text{Cumulative net mineralized soil N (CMN, kg ha}^{-1}) = \text{soil mineral N (kg ha}^{-1}) + \text{CNY at N}_0 \text{ (kg ha}^{-1})$$

Cumulative net mineralized soil N was determined at each depth for plots receiving no N fertilization ($N_0$), and summed across successive harvests. Concentrations were based on an average bulk density of 1.47 g cm$^{-3}$ for a 0- to 50-cm depth profile of a Leadvale silt loam (Buell et al., 2004).

$$\text{Cumulative fertilizer N (CFN) recovery (\%)} = 100 \text{ (CNY at N}_x - \text{CNY at N}_0\text{, kg ha}^{-1})/\text{CFN (kg ha}^{-1})$$

Cumulative fertilizer N recovery was calculated at each harvest for each plot receiving N fertilizer ($N_x$), where CFN was the sum of fertilizer N applied before harvest.

Sites were analyzed separately as randomized complete block designs using a mixed linear model, PROC MIXED (Littell et al., 1996; SAS Institute, 1998) for analysis of variance of CHY, CMN, and CFN recovery. Covariance parameters were estimated by restricted maximum likelihood (Littell et al., 1996). Fixed effects for CHY were harvest (4 df), N rate (5 df), and the interaction (20 df). The fixed effect for CMN was harvest (4 df). Fixed effects for CFN recovery were harvest (4 df), N rate (4 df), and the interaction (16 df). Replication (2 df) and its interactions with fixed effects were random. Denominator df were calculated by a general Satterthwaite approximation method (Littell et al., 1996). Parameter estimates from regression were compared by 95% confidence limits (Freund and Littell, 2000). Means were separated using the Tukey HSD test at $P \leq 0.05$ (SAS Institute, 1998). Use of the word significant implies a $P \leq 0.05$.

## RESULTS AND DISCUSSION

Total rainfall for the 2002 growth interval (861 mm) was slightly greater than the long-term mean of 816 mm. There was less rainfall in 2003 (529 mm) than 2002, and less rainfall than the long-term mean in all months except June and August (Fig. 2). Air temperatures differed little from the long-term mean.

The PAR response for the 8-mo growth interval in the meadow was best described by fifth- and fourth-degree polynomial equations for 2002 and 2003, respectively, and parameter estimates differed significantly for 2002 and 2003 (Fig. 3). The PAR response in the pine alley was described by fourth-degree equations in 2002

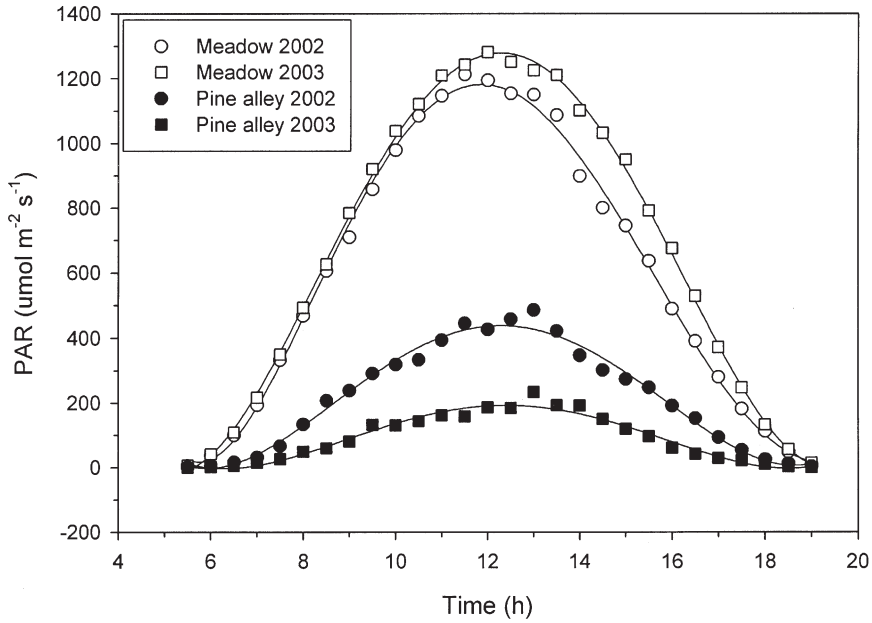


**Fig. 3. Diurnal trend of photosynthetically active radiation (PAR) in a meadow and pine alley for the March to October growth interval. Regression equations for the meadow were $Y = 11700 - 5650X + 980X^2 - 74.4X^3 + 2.54X^4 - 0.0317X^5$, $R^2 = 0.99$ (2002) and $Y = 5530 - 2680X + 432X^2 - 26.3X^3 + 0.536X^4$, $R^2 = 0.99$ (2003). Regression equations for the pine alley were $Y = 3270 - 1460X + 222X^2 - 13.2X^3 + 0.269X^4$, $R^2 = 0.98$ (2002) and $Y = 1910 - 816X + 120X^2 - 7.01X^3 + 0.142X^4$, $R^2 = 0.96$ (2003). Equations were significant at $P = 0.001$.**

and 2003 that did not differ significantly. Mean daily (and total daily) PAR in the meadow differed significantly for 2002 (584 $\mu$mol m$^{-2}$ s$^{-1}$ or 30 mol m$^{-2}$ d$^{-1}$) and 2003 (657 $\mu$mol m$^{-2}$ s$^{-1}$ or 34 mol m$^{-2}$ d$^{-1}$). Solar irradiance in the meadow was typical (20–40 mol m$^{-2}$ d$^{-1}$) for unshaded environments at approximately this latitude (Chirko et al., 1996). Conversely, mean PAR in the pine alley was 206 $\mu$mol m$^{-2}$ s$^{-1}$ (11 mol m$^{-2}$ d$^{-1}$) in 2002 and 86 $\mu$mol m$^{-2}$ s$^{-1}$ (4 mol m$^{-2}$ d$^{-1}$) in 2003. For any given year, total daily PAR in the pine alley was only 12 to 37% of the meadow.

Annual changes in mean PAR could be caused by atmospheric conditions and increased solar interception by the canopy due to tree growth. Number of cloudy days was not known, but there were 65 d with rain in 2002 compared to 52 in 2003 (NOAA, 2002b; 2003). Total solar radiation for the 8-mo growth interval varied as much as 11% between 1961 and 1990 at Fort Smith, AR, 64 km west of Booneville (NOAA, 1993). Mean tree height increased significantly from 7.5 m in 2002 to 8.8 m in 2003, and basal area increased significantly from 18 m$^2$ ha$^{-1}$ (2002) to 24 m$^2$ ha$^{-1}$ (2003). Shading can decrease net photosynthesis of understory herbage (Awada et al., 2003).

There was a putative fragipan at 40- to 60-cm depth at both sites. Leadvale soil series usually has a perched water table in spring (USDA-SCS, 1980) that occasionally reached the soil surface. The moist fragipan was easily penetrated by the hydraulic soil probe in May and June, but it was impenetrable in October. We observed very few plant roots in soil cores at depths $\geq$ 40 cm.

Volumetric soil water decreased across the 8-mo growth interval (Fig. 4). Parameter estimates for regression coefficients had overlapping confidence limits in 2002, indicating that soil water was depleted at similar rates in the meadow and pine alley. Soil water depletion was more rapid in the pine alley than the meadow in 2003. There was less rainfall in 2003 than 2002 (Fig. 2), and rainfall interception by the tree canopy could increase evapotranspiration demands of the pine alley (Tournebize et al., 1996). Mean soil water did not differ significantly between years in the meadow (0.30 cm$^3$ cm$^{-3}$), while in the pine alley mean soil water was significantly greater in 2002 (0.25 cm$^3$ cm$^{-3}$) than 2003 (0.21 cm$^3$ cm$^{-3}$). Herbage at both sites appeared stressed by high air temperatures and inadequate soil water especially in late July through September (weeks 30–40). Yield of alley cropped herbage usually is affected more by insufficient soil water than by shade (Harrington et al., 2003; Jose et al., 2000). Root elongation of loblolly pine decreases significantly after July in the Gulf Coastal Plain (Sword and Tiarks, 2002). At this density, tree diameter growth probably is affected when soil water is less than 0.15 cm$^3$ cm$^{-3}$ (Bassett, 1964).

Preliminary tests indicated that sites initially had relatively low fertility (pH 5.9 and 5.3, 4.5 and 6.5 $\mu$g P g$^{-1}$, 68 and 58 $\mu$g K g$^{-1}$, and 4.5 and 0.6 $\mu$g $NO_3$–N g$^{-1}$ for meadow and pine alley, respectively). Extractable Al increased with depth at both sites, while available P and pH decreased with depth (Table 1). Available P was very low regardless of site or depth despite receiving annual broadcast applications of 100 kg P ha$^{-1}$ in December 2001 and 2002. The fragipan probably accentuated competition for water and nutrients by reducing the effective soil volume for root exploration.

The date $\times$ depth interaction was significant for total soil N and C in the meadow (Table 2). Total N and C decreased with depth in the meadow. At any given depth total N increased from 2002 to 2003 probably due to N

**Table 1. Soil chemical properties of sites in May 2002. Values are overall means across plots that would receive six N rates ranging from 0 to 500 kg N $ha^{-1}$ $yr^{-1}$ in 100 kg N $ha^{-1}$ increments. In March 2002, plots were treated with one-third of the yearly total fertilizer N; remaining N for the year was applied after collecting the soil samples in May 2002.†**

| Site | Depth | Extractable Al | Available P | pH |
|---|---|---|---|---|
| | cm | μg $g^{-1}$ | | |
| Meadow | 0–10 | 2.1c | 3.59a | 5.4a |
| | 10–30 | 27.1b | 0.47b | 5.3b |
| | 30–60 | 100.9a | 0.64b | 5.0c |
| Pine alley | 0–10 | 8.2c | 6.05a | 5.6a |
| | 10–30 | 38.8b | 1.09b | 5.0b |
| | 30–60 | 94.0a | 1.67b | 4.8c |

† Means within a site followed by a common letter do not differ by Tukey HSD ($P > 0.05$).

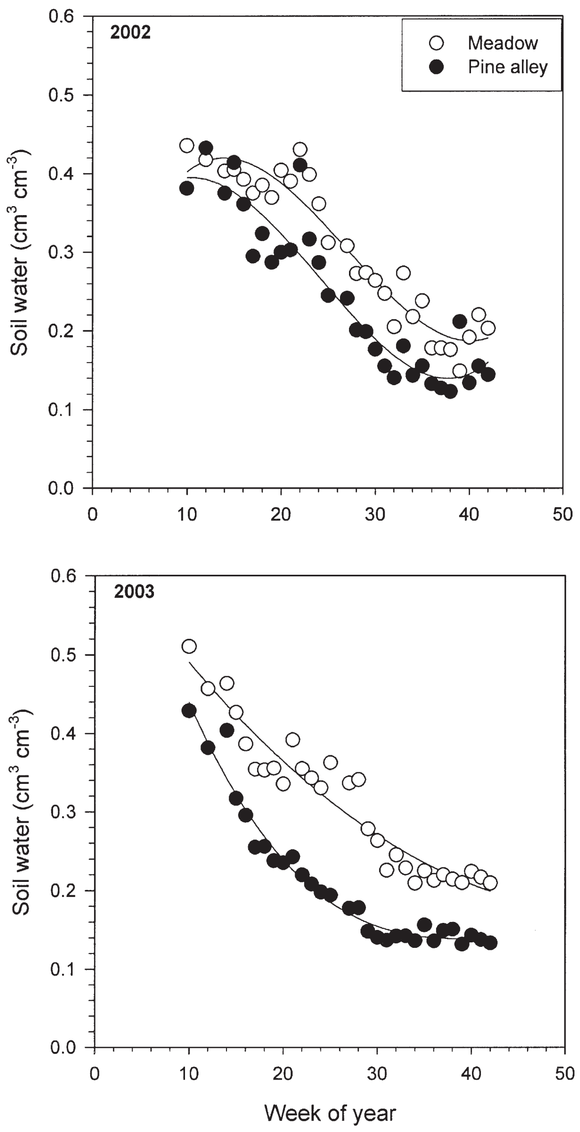

Fig. 4. Volumetric soil water during the 2002 and 2003 growing seasons in a meadow and pine alley. Regression equations in 2002 were $Y = (1.53 \times 10^{-1}) + (4.34 \times 10^{-2})X - (2.10 \times 10^{-3})X^2 + (2.59 \times 10^{-5})X^3$, $R^2 = 0.91$ (meadow) and $Y = (2.53 \times 10^{-1}) + (2.99 \times 10^{-2})X - (1.83 \times 10^{-3})X^2 + (2.53 \times 10^{-5})X^3$, $R^2 = 0.87$ (pine alley). Regression equations in 2003 were $Y = (6.11 \times 10^{-1}) + (1.54 \times 10^{-2})X + (1.37 \times 10^{-4})X^2$, $R^2 = 0.90$ (meadow) and $Y = (7.90 \times 10^{-1}) + (4.89 \times 10^{-2})X - (1.26 \times 10^{-3})X^2 - (1.10 \times 10^{-5})X^3$, $R^2 = 0.96$ (pine alley). Equations were significant at $P = 0.001$.

**Table 2. Soil total N and C with depth in a meadow and loblolly pine alley in May 2002 and October 2003. Values are overall means across plots receiving six N rates ranging from 0 to 500 kg N $ha^{-1}$ $yr^{-1}$ in 100 kg N $ha^{-1}$ increments. In 2002 and 2003, N fertilizer was broadcast as three equal splits in March, May, and September.†**

| Site | Date | Depth | Total N | Total C |
|---|---|---|---|---|
| | | cm | g $kg^{-1}$ | |
| Meadow | May 2002 | 0–10 | 1.89b | 20.20b |
| | | 10–30 | 1.02d | 9.11c |
| | | 30–60 | 0.78f | 5.66d |
| | October 2003 | 0–10 | 2.14a | 22.82a |
| | | 10–30 | 1.12c | 9.96c |
| | | 30–60 | 0.87e | 6.24d |
| Pine alley | May 2002 | 0–10 | 1.38 | 15.60 |
| | | 10–30 | 0.60 | 5.52 |
| | | 30–60 | 0.55 | 3.61 |
| | October 2003 | 0–10 | 1.44 | 15.30 |
| | | 10–30 | 0.67 | 5.78 |
| | | 30–60 | 0.63 | 3.92 |

† Means within a site followed by a common letter do not differ by Tukey HSD ($P > 0.05$). Means for total N and C in the pine alley were not compared because the date × depth interaction was not significant ($P \geq 0.05$).

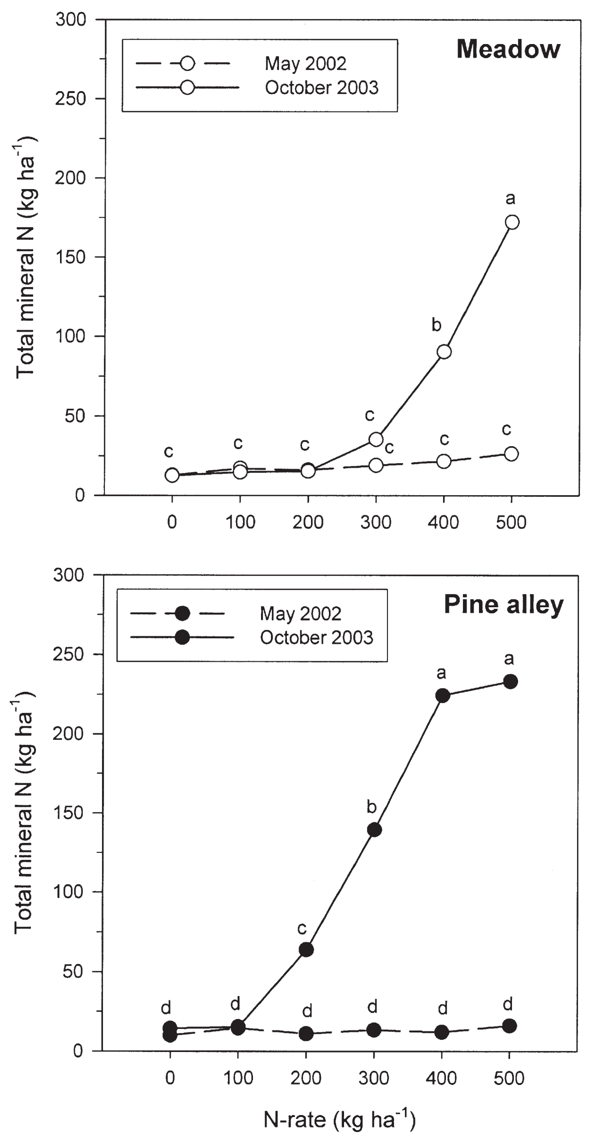

Fig. 5. Effect of fertilizer N on total mineral N in the 0- to 60-cm soil profile for meadow and loblolly pine alley sites in May 2002 and October 2003. A single letter was used to label data points when means overlapped. Means within sites with different letters differ by Tukey HSD ($P \leq 0.05$).

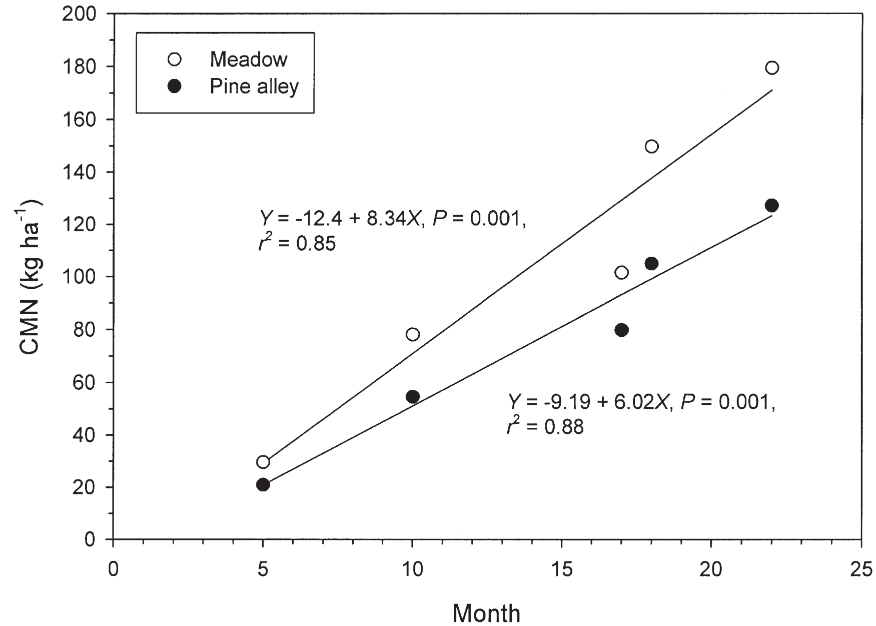


**Fig. 6. Cumulative net mineralized soil N (CMN) in a meadow and pine alley. Harvests were designated by month: May 2002 = 5, October 2002 = 10 . . . October 2003 = 22 for regression.**



fertilization. Total C increased significantly from 2002 to 2003 at 0 to 10 cm, but did not differ significantly between years at other depths. In the pine alley, total N was greatest at 0 to 10 cm (1.41 g $kg^{-1}$) and decreased significantly at 10 to 30 cm (0.64 g $kg^{-1}$) and 30 to 60 cm (0.59 g $kg^{-1}$). Similarly, total soil C decreased significantly with depth in the pine alley from 15.44 g $kg^{-1}$ at 0 to 10 cm, 5.65 g $kg^{-1}$ at 10 to 30 cm, and 3.77 g $kg^{-1}$ at 30 to 60 cm. A decrease in organic matter and pH with depth, and increase of extractable Al, was consistent for fragipan-containing soils (Rhoton and Tyler, 1990).

The date $\times$ N rate interaction was significant for total mineral N at both sites. Total mineral N did not differ significantly with N rate at either site in 2002 (Fig. 5). In 2003, there was substantial accumulation of mineral N in the meadow (90–172 kg $ha^{-1}$) at $\geq$400 kg N $ha^{-1}$ $yr^{-1}$ and pine alley (64–233 kg $ha^{-1}$) at $\geq$200 kg N $ha^{-1}$ $yr^{-1}$, indicating that fertilizer N was not limiting for herbage or tree growth at these respective rates.

Cumulative net mineralized soil N increased nearly sixfold at each site from May 2002 to October 2003 (Fig. 6), and slopes did not differ significantly between sites. Silvopastoral soil in a short-term laboratory study had more rapid in situ N mineralization than a pasture soil, which was attributed to greater soil organic matter and biological activity (Sierra et al., 2002). Conversely, afforestation reduces net N mineralization compared to nonforested pasture (Ross et al., 2002). Our values for CMN were markedly less than reported (170–325 kg $ha^{-1}$ $yr^{-1}$) for Monterey pine (*P. radiata* D. Don) silvopastures in New Zealand (Amatya et al., 2002; Parfitt et al., 2003). Low CMN values may reflect the low native fertility or low soil organic matter of the Leadvale silt loam. Mineralization can be enhanced by herbicide treatment of pasture (Parfitt et al., 2003). Further, CMN values represent a lower limit because total CNY was underestimated and mineralized N accumulation by the trees at the pine alley site was not measured.

Tall fescue was the predominant herbage species, averaging about 90 and 70% of the estimated herbage biomass in spring and fall, respectively. Bermudagrass [*Cynodon dactylon* (L.) Pers.], panicum (*Panicum* spp.), and purpletop [*Tridens flavus* (L.) Hitchc.] were common weedy grasses, and horsenettle (*Solanum carolinense* L.) was a common weedy forb in the pine alley. Annual bluegrass (*Poa annua* L.), broomsedge (*Andropogon virginicus* L.), and foxtail (*Setaria* spp.) were common weedy grasses, and clover (*Trifolium* L. spp.), horsenettle, persimmon (*Diospyros virginiana* L.), and trumpetcreeper [*Campsis radicans* (L.) Seem.] were common weedy forbs in meadow plots.

Cumulative herbage yield increased nearly sixfold in the meadow and 4.5-fold in the pine alley from May 2002 to October 2003 (Fig. 7A). During the 22-mo experimental period, mean CHY was 9400 $\pm$ 588 kg $ha^{-1}$ ($\pm$ SE, $n$ = 90) in the meadow and 3670 $\pm$ 198 kg $ha^{-1}$ in the pine alley across harvests and N rates, showing that there was sufficient herbage base for rotational grazing by livestock. Herbage yield in the meadow increased about 12.8 kg dry matter per kg N applied at $\leq$300 kg N $ha^{-1}$ $yr^{-1}$, before appearing to plateau (Fig. 7B). In the pine alley, CHY increased linearly at about 4.2 kg dry matter per kg N applied. Thus, the meadow was much more responsive to added N than the pine alley at $\leq$300 kg N $ha^{-1}$ $yr^{-1}$.

The decrease in herbage yield in the pine alley compared to the meadow could be a function of canopy closure. Canopy closure occurs in densely planted tree stands when the area of the tree canopy projected onto the ground surface reaches a point at which there is minimal light penetration and herbage production (Knowles et al., 1999). Canopy closure of *P. radiata* increases asymp-

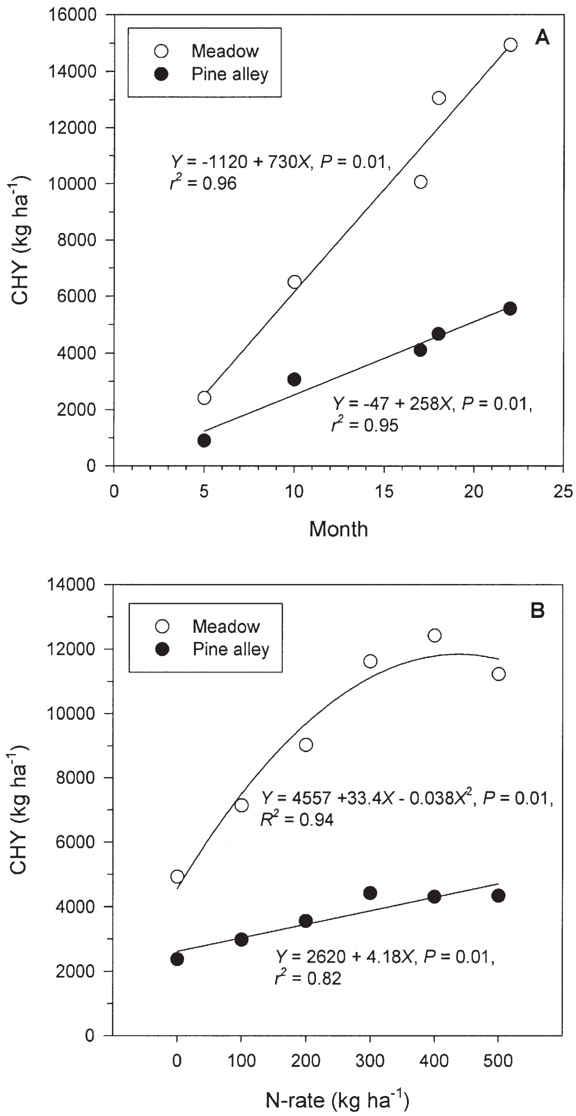


**Fig. 7. (A) Effect of the harvest × (B) N rate interaction on cumulative herbage yield (CHY) in a meadow and pine alley. Harvests were designated by month: May 2002 = 5, October 2002 = 10 . . . October 2003 = 22 for regression (A).**

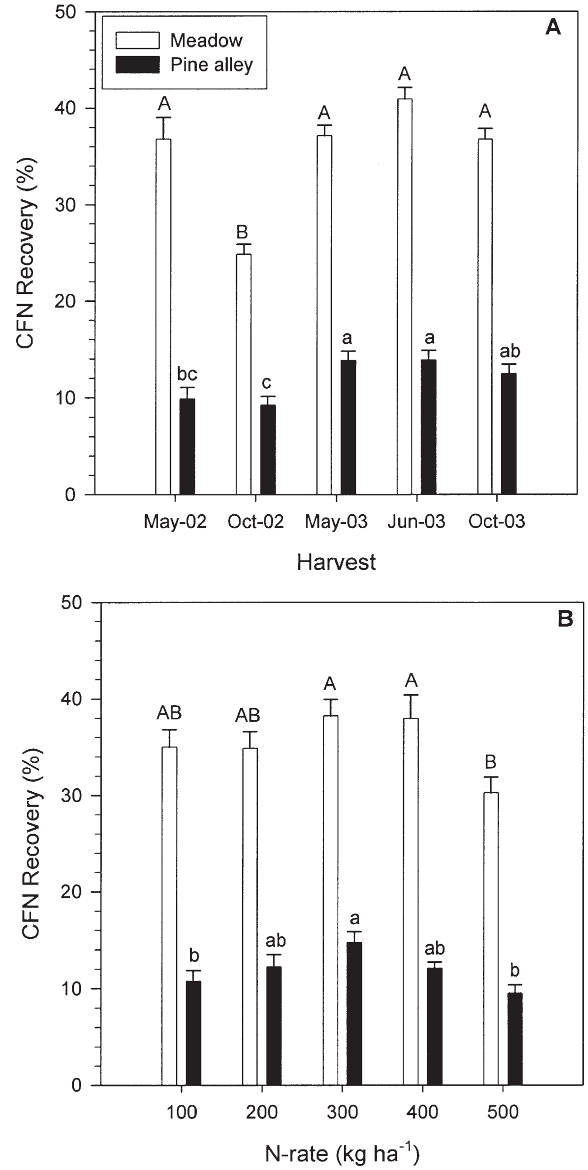


**Fig. 8. (A) Harvest and (B) N effects on cumulative fertilizer N (CFN) recovery. Lines at each bar are the standard error of the mean ($n$ = 15). Means within sites with different letters differ by Tukey HSD ($P \leq 0.05$).**

totically with basal area, reaching a maximum of 80% closure at about 40 m$^2$ ha$^{-1}$ (Knowles et al., 1999). Herbage productivity is inversely related to canopy closure, with the model predicting zero herbage production at 70% canopy closure (Knowles et al., 1999). Assuming a 70% unpruned crown length for this loblolly pine stand, the model by Knowles et al. (1999) predicted that the canopy was about 40% closed, and herbage productivity was about 40% of the meadow. This compared well to actual data that CHY of the pine alley was 39%, and that PAR was 12 to 37% of the meadow. Herbage production in the pine alley might have been greater had trees been planted at lower density (Burner and Brauer, 2003; Garrett and McGraw, 2000; Robinson and Clason, 2000) to delay canopy closure. Tree thinning could diminish environmental constraints of the pine alley, but costs probably would exceed return from sale of wood fiber at this early stage of the tree rotation.

There were significant effects of harvest and N rate on herbage CFN recovery at both sites, but the harvest × N rate interaction was not significant ($P \geq 0.50$). The herbage CFN recovery varied little across harvests, except for a decrease at both sites in October 2002 (Fig. 8A). Herbage CFN recovery was numerically greatest at 300 and 400 kg N ha$^{-1}$ in the meadow (Fig. 8B) and was greater at 300 kg N ha$^{-1}$ than at 100 or 500 kg N ha$^{-1}$ in the pine alley. Averaged across harvests and N rates, herbage CFN recovery was 38% ± 0.88 (mean ± SE, $n$ = 75) in the meadow, nearly three times that in the pine alley (12% ± 0.49). Total fertilizer N recovery in the pine alley would undoubtedly be greater if fertilizer N uptake by loblolly pine trees had been measured.

Herbage CFN recovery for the meadow was consistent with the 34% maximum N recovery for tall fescue pasture on a deep acidic soil with large water holding capacity, while that for the pine alley was comparable to a shallow soil (15–18%) with low water holding capacity (Staley et al., 1991). Herbage–tree competition for light, soil water, and soil nutrients probably contributed to the poor N recovery of the pine alley. Rainfall, air temperature (Fig. 2), soil water (Fig. 4), or tall fescue botanical composition during the May to October growth interval did not appear to affect response of herbage CFN recovery at either site (Fig. 8).

## CONCLUSIONS

Abundant herbage production can be difficult to achieve in agroforestry systems on marginal sites because of crop–tree competition for limited growth resources. Tall fescue has an economically optimum N rate of 368 kg $ha^{-1}$ and can recover as much as 47 to 74% of fertilizer N with intensive management in conventional agricultural systems (Hall et al., 2003). The meadow and pine alley had sufficient herbage yield for livestock production, and herbage N fertilization needs were met at $\leq$300 kg $ha^{-1}$ in the meadow and at $\leq$200 kg $ha^{-1}$ in the pine alley (Fig. 5, 7). Herbage CFN recovery in the meadow and pine alley was only 38 and 12%, respectively, substantially less at each site than reported by Hall et al. (2003). At both sites, low fertilizer N recovery by the herbage could be attributed to the shallow fragipan soil, late season depletion of soil water, and possibly low level of available soil P. The high tree density (995 trees $ha^{-1}$) at the pine alley site reduced solar reception by the understory herbage causing further imbalance in the competition for resources. Results were consistent with low N recoveries on acidic soils of the humid Northeast (Staley et al., 1991). Yearly applications of fertilizer N $>$ 300 kg $ha^{-1}$ $yr^{-1}$ are not recommended for the meadow due to poor herbage N recovery and lack of N response at higher N rates. Similarly, there was no significant increase in herbage CFN recovery in the pine alley at N rates $>$ 300 kg $ha^{-1}$. The small, but significant incremental increase in CHY between 100 and 300 kg N $ha^{-1}$ in the pine alley might not justify the additional cost of N fertilizer either for hay or grazing (Taylor et al., 2004) and potential environmental consequences of a substantial buildup of mineral N in the soil. Thus, only maintenance levels ($\leq$100 kg $ha^{-1}$) of N fertilization should be applied to the pine alley.

## ACKNOWLEDGMENTS

Dr. Henry Pearson (USDA-ARS, retired) designed and planted the loblolly pine study area. The technical assistance of K. Chapman and J. Whiley (USDA-ARS, Booneville, AR) and J. Weik (USDA-ARS, El Reno, OK) is gratefully acknowledged. Edgar Mersiovsky (USDA-NRCS, Little Rock, AR) provided the hydraulic soil sampler.

## REFERENCES

Amatya, G., S.X. Chang, M.H. Beare, and D.J. Mead. 2002. Soil properties under a *Pinus radiata*–ryegrass silvopastoral system in New Zealand. Part II. C and N of soil microbial biomass, and soil N dynamics. Agrofor. Syst. 54:149–160.

Avery, T.E., and H.E. Burkhart. 1994. Forest measurements. 4th ed. McGraw-Hill, New York.

Awada, T., M.E.L. Perry, and W.H. Schacht. 2003. Photosynthetic and growth responses of the $C_3$ *Bromus inermis* and the $C_4$ *Andropogon gerardii* to tree canopy cover. Can. J. Plant Sci. 83:533–540.

Bassett, J.R. 1964. Diameter growth of loblolly pine trees as affected by soil-moisture availability. Res. Paper SO-9. USDA, For. Serv., South. For. Exp. Stn., New Orleans, LA.

Brauer, D., D. Burner, and M. Looper. 2004. Effects of tree configuration on the understory productivity of a loblolly pine-forage agroforestry practice. Am. Forage Grassl. Counc. Proc. 13:412–416.

Buell, G.R., H.W. Markewich, R. Kulisek, S. Pollard, and T.T. Cook. 2004. Site-specific soil-carbon (S3C) database for mineral soils of the Mississippi River basin, USA. USGS open-file report 2004–1227, v. 1.0 [Online]. Available at pubs.usgs.gov/of/2004/1227/ (accessed 30 Sept. 2004; verified 16 Apr. 2005). USGS, Atlanta, GA.

Burner, D.M. 2003. Influence of alley crop environment on orchardgrass and tall fescue herbage. Agron. J. 95:1163–1171.

Burner, D.M., and D.K. Brauer. 2003. Herbage response to spacing of loblolly pine trees in a minimal management silvopasture in southeastern USA. Agrofor. Syst. 57:67–75.

Chirko, C.P., M.A. Gold, P.V. Nguyen, and J.P. Jiang. 1996. Influence of direction and distance from trees on wheat yield and photosynthetic photon flux ($Q_p$) in a *Paulownia* and wheat intercropping system. For. Ecol. Manage. 83:171–180.

Clason, T.R. 1999. Silvopastoral practices sustain timber and forage production in commercial loblolly pine plantations of northwest Louisiana, USA. Agrofor. Syst. 44:293–303.

Devkota, N.R., and P.D. Kemp. 1998–1999. Morphological aspects of pasture species in the shade in relation to various management practices under silvopastoral systems. J. Inst. Agric. Anim. Sci. 19–20:1–26.

Dougan, W.K., and A.L. Wilson. 1974. The absorptiometric determination of aluminium in water. A comparison of some chromogenic reagents and the development of an improved method. Analyst 99:413–430.

Freund, R.J., and R.C. Littell. 2000. SAS System for Regression, 3rd ed. SAS Institute Inc., Cary, NC.

Fribourg, H.A., G.R. Wells, H. Calonne, E. Dujardin, D.D. Tyler, J.T. Ammons, R.M. Evans, A. Houston, M.C. Smith, M.E. Timpson, and G.G. Percell. 1989. Forage and tree production on marginal soils in Tennessee. J. Prod. Agric. 2:262–268.

Garrett, H.E., and R.L. McGraw. 2000. Alley cropping practices. p. 149–188. *In* H.E. Garrett et al. (ed.) North American agroforestry: An integrated science and practice. ASA, Madison, WI.

Givnish, T.J. 1988. Adaptation to sun and shade: A whole-plant perspective. Aust. J. Plant Physiol. 15:63–92.

Grado, S.C., C.H. Hovermale, and D.G. St. Louis. 2001. A financial analysis of a silvopasture in southern Mississippi. Agrofor. Syst. 53:313–322.

Haggar, J.P., E.V.J. Tanner, J.W. Beer, and D.C.L. Kass. 1993. Nitrogen dynamics of tropical agroforestry and annual cropping systems. Soil Biol. Biochem. 25:1363–1378.

Hall, M.H., D.B. Beegle, R.S. Bowersox, and R.C. Stout. 2003. Optimum nitrogen fertilization of cool-season grasses in the northeast USA. Agron. J. 95:1023–1027.

Harrington, T.B., C.M. Dagley, and M.B. Edwards. 2003. Above- and belowground competition from longleaf pine plantations limits performance of reintroduced herbaceous species. For. Sci. 49: 681–695.

Harwell, R.L., and C.W. Dangerfield, Jr. 1991. Multiple use on marginal land: A case for cattle and loblolly pine. For. Chron. 67: 249–253.

Haynes, R.W. 2003. An analysis of the timber situation in the United States: 1952–2050. Gen. Tech. Rep. PNW-GTR-560. USDA, For. Serv., Portland, OR.

Jose, S., A.R. Gillespie, J.R. Seifert, and D.J. Biehle. 2000. Defining competition vectors in a temperate alley cropping system in the midwestern USA. 2. Competition for water. Agrofor. Syst. 48:41–59.

Knowles, R.L., G.C. Horvath, M.A. Carter, and M.F. Hawke. 1999. Developing a canopy closure model to predict overstorey/understorey relationships in *Pinus radiata* silvopastoral systems. Agrofor. Syst. 43:109–119.

Lewis, C.E., and H.A. Pearson. 1987. Agroforestry using tame pastures under planted pines in the southeastern United States. p. 195–212. *In* H. Gholz (ed.) Agroforestry: Realities, possibilities, and potentials. Martinus Nijhoff Publ., Dordrecht, the Netherlands.

Lin, C.H., R.L. McGraw, M.F. George, and H.E. Garrett. 1999. Shade effects on forage crops with potential in temperate agroforestry practices. Agrofor. Syst. 44:109–119.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS System for Mixed Models. SAS Institute Inc., Cary, NC.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of the Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

NOAA. 1993. Solar and meteorological surface observation network, 1961–1990. Vol. 2, Central US. NOAA, Natl. Climatic Data Cent., Asheville, NC.

NOAA. 2002a. Climatography of the United States No. 81, Arkansas. NOAA, Natl. Climatic Data Cent., Asheville, NC.

NOAA. 2002b. Climatological data for Arkansas. Vol. 107(03) to 107(10). NOAA, National Climatic Data Cent., Asheville, NC.

NOAA. 2003. Climatological data for Arkansas. Vol. 108(03) to 108(10). NOAA, National Climatic Data Cent., Asheville, NC.

Parfitt, R.L., D.J. Ross, and L.F. Hill. 2003. Soil nitrogen mineralisation changes rapidly when pine is planted into herbicide-treated pasture– the first two years of growth. Aust. J. Soil Res. 41:459–469.

Pearcy, R.W. 1990. Sunflecks and photosynthesis in plant canopies. Annu. Rev. Plant Physiol. Plant Mol. Biol. 41:421–453.

Rhoton, F.E., and D.D. Tyler. 1990. Erosion-induced changes in the properties of a fragipan soil. Soil Sci. Soc. Am. J. 54:223–228.

Robinson, J.L., and T. Clason. 2000. From a pasture to a silvopasture system. Agroforestry Note 22, USDA Natl. Agrofor. Cent., Univ. of Nebraska, Lincoln, NE.

Ross, D.J., K.R. Tate, N.A. Scott, R.H. Wilde, N.J. Rodda, and J.A. Townsend. 2002. Afforestation of pastures with *Pinus radiata* influences soil carbon and nitrogen pools and mineralisation and microbial properties. Aust. J. Soil Res. 40:1303–1318.

Saggar, S., C.B. Hedley, and G.J. Salt. 2001. Soil microbial biomass, metabolic quotient, and carbon and nitrogen mineralisation in 25-year-old *Pinus radiata* agroforestry regimes. Aust. J. Soil Res. 39: 491–504.

SAS Institute. 1998. SAS/STAT user's guide. Release 7.00. Windows version 4.10.1998. SAS Inst., Cary, NC.

Schultz, R.P. 1997. Loblolly pine. USDA, For. Serv., Agric. Hndbk. 713. U.S. Gov. Print. Office, Washington, DC.

Sierra, J., M. Dulormne, and L. Desfontaines. 2002. Soil nitrogen as affected by *Gliricidia sepium* in a silvopastoral system in Guadeloupe. French Antilles. Agrofor. Syst. 54:87–97.

Staley, T.E., W.L. Stout, and G.A. Jung. 1991. Nitrogen use by tall fescue and switchgrass on acidic soils of varying water holding capacity. Agron. J. 83:732–738.

Stout, W.L., and G.A. Jung. 1992. Influences of soil environment on biomass and nitrogen accumulation rates of orchardgrass. Agron. J. 84:1011–1019.

Sword, M.A., and A.E. Tiarks. 2002. Local soils information needed to define the root zone in process models on the Gulf Coastal Plain. Gen. Tech. Rep. SRS-58. USDA, For. Serv., South. Res. Stn., Asheville, NC.

Taylor, M., K.C. Dhuyvetter, and T.L. Kastens. 2004. Estimating the costs of managed haying or grazing of CRP. MF-2657. Kansas State Univ., Dep. Ag. Econ., Manhattan, KS.

Tecator. 1983. Application note (AN 62/83): Determination of the sum of nitrate and nitrite in water by flow injection analysis. Foss Tecator AB, Höganäs, Sweden.

Tecator. 1984. Application note (AN 50/84): Determination of ammonia nitrogen by flow injection analysis and gas diffusion. Foss Tecator AB, Höganäs, Sweden.

Tournebize, R., H. Sinoquet, and F. Bussiere. 1996. Modeling evapotranspiration partitioning in a shrub/grass crop. Agric. For. Meteorol. 81:255–272.

USDA-NASS. 2002. 2002 Agricultural statistics [Online]. Available at www.usda.gov/nass/pubs/agr02/acro02.htm (accessed 13 Mar. 2003; verified 16 Apr. 2005). USDA-NASS, Washington, DC.

USDA-SCS. 1980. Soil survey of Logan County, Arkansas. USDA-SCS, U.S. Gov. Print. Office, Washington, DC.

Vanotti, M.B., and L.G. Bundy. 1994. Frequency of nitrogen fertilizer carryover in the humid Northeast. Agron. J. 86:881–886.

Zemenchik, R.A., and K.A. Albrecht. 2002. Nitrogen use efficiency and apparent nitrogen recovery of Kentucky bluegrass, smooth bromegrass, and orchardgrass. Agron. J. 94:421–428.

Zinkhan, F.C., and D.E. Mercer. 1997. An assessment of agroforestry systems in the southern USA. Agrofor. Syst. 35:303–321.